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Language Processing Fluency and Verbal Working Memory in Prelingually-Deaf Long-Term Cochlear Implant Users: A Pilot Study

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Abstract

Objective: Verbal working memory (WM) is more strongly correlated with spoken language skills in prelingually deaf, early-implanted cochlear implant (CI) users than in normal-hearing peers, suggesting that CI users access WM in order to support and compensate for their slower, more effortful spoken language processing. This pilot study tested the feasibility and validity of a dual-task method for establishing the causal role of WM in basic language processing (lexical access speed) in samples of 9 CI users (ages 8-26 years) and 9 normal-hearing peers.

Methods: Participants completed tests of lexical access speed (rapid automatized picture naming test and lexical decision test) under two administration conditions: a standard condition and a dual-task WM condition requiring participants to hold numerals in working memory during completion of the lexical access speed tests.

Results: CI users showed more dual-task interference (decline in speed during the WM condition compared to the standard condition) than normal-hearing peers, indicating that their lexical access speed was more dependent on engagement of WM resources. Furthermore, dual-task interference scores were significantly correlated with several measures of speed-based executive functioning, consistent with the hypothesis that the dual-task method reflects the involvement of executive functioning in language processing.

Conclusion: These pilot study results support the feasibility and validity of the dual-task WM method for investigating the influence of WM in the basic language processing of CI users. Preliminary findings indicate that CI users are more dependent on use of WM as a compensatory strategy during slow-effortful basic language processing than normal-hearing peers.

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Keywords

cochlear implant; language; working memory; executive functioning; deafness

The benefits of cochlear implants (CIs) for restoring hearing and supporting the development of spoken language skills in prelingually deaf children are well-established (Geers & Nicholas, 2013; Wilson & Dorman, 2008). However, significant variability in speech and language outcomes is routinely observed in this population, and a subgroup of children with CIs fail to attain optimal speech-language outcomes (Niparko et al., 2010; Pisoni et al., 2008). Identification of factors explaining this variability in spoken language outcomes is critical for understanding and developing novel, targeted interventions to improve speech-language skills following cochlear implantation (Kronenberger & Pisoni, 2016, in press; Pisoni, Kronenberger, Chandramouli, & Conway, 2016).

Recent research has shown that children with CIs are at risk for delays in executive functioning (EF), the neurocognitive processes involved in focusing, controlling, and executing thinking and behaviour so that goals can be achieved (Kronenberger, Pisoni, Henning, & Colson, 2013). EF is a multifactorial construct, consisting of subdomains including controlled attention (focused, directed attention), working memory (WM; memory concurrent with other processing demands), inhibition (withholding behavior to allow thinking), flexibility (shifting focus and strategies), and controlled cognitive fluency (processing information quickly under conditions requiring concentration). Children with CIs have been found to show greater rates of delay than normal-hearing peers in multiple subdomains of EF (Figueras, Edwards, & Langdon, 2008), including inhibition (Kronenberger, Beer, Castellanos, Pisoni, & Miyamoto, 2014) and controlled cognitive fluency (Kronenberger et al., 2013), but the largest and most consistent delays have been found in verbal WM (Kronenberger et al., 2013). Studies of verbal WM have consistently found shorter span-based verbal memory (word span, digit span, etc.) in children with CIs relative to normal-hearing peers (Kronenberger, Colson, Henning, & Pisoni, 2014; Lyxell et al., 2008; Nittrouer, Caldwell-Tarr, & Lowenstein, 2013; Nittrouer, Caldwell, Lowenstein, Tarr, & Holloman, 2012; Ortmann et al., 2013; Pisoni & Cleary, 2003; Pisoni, Kronenberger, Roman, & Geers, 2011), regardless of modality of stimulus presentation (spoken vs. visual) (AuBuchon, Pisoni, & Kronenberger, 2015; Kronenberger et al., 2013). These delays in span-based working memory are found at all ages and persist longitudinally (Harris et al., 2013).

Delays in EF found in children with CIs are hypothesized to result from delays in exposure to sound and spoken language experiences (Kronenberger & Pisoni, 2016). Specifically, in cross-sectional, correlational studies, strong links have been demonstrated between EF and speech-language development and outcomes in prelingually deaf children with CIs. For example, Figueras et al. (Figueras et al., 2008) found strong correlations between EF and language composite scores in a sample of children with CIs and hearing aids as well as in a sample of normal-hearing (NH) children. Furthermore, the observed EF differences between the two samples were no longer significant when language was statistically controlled.

However, because these studies were correlational, direction of causality could not be definitively determined.

Other correlational studies have examined relationships between specific components of EF and speech-language skills in children with CIs. Kronenberger et al. (Kronenberger, Colson, et al., 2014) found significant correlations between EF subdomains (verbal WM, spatial WM, inhibition-concentration, fluency-speed) and speech-language skills, but in different ways for children with CIs compared to NH children. For children with CIs, verbal WM and fluency-speed related to speech perception and language skills, whereas for NH children, verbal WM, spatial WM, and inhibition-concentration were correlated significantly with language skills. However, the subdomain of EF most consistently correlated with language outcomes in children with CIs is verbal WM. Verbal WM is related to vocabulary (Geers, Pisoni, & Brenner, 2013; Nittrouer et al., 2013; Pisoni et al., 2011; Wass et al., 2008), novel word learning (Willstedt-Svensson, Löfqvist, Almqvist, & Sahlén, 2004), reading (Geers et al., 2013), and speech perception outcomes (Nittrouer et al., 2013; Pisoni et al., 2011) in CI users. Furthermore, evidence suggests that verbal WM is more strongly related to speech perception and language outcomes in CI users than in NH peers (Kronenberger, Colson, et al., 2014; Lyxell et al., 2008; Nittrouer et al., 2013; Wass et al., 2008).

The causal relationship between language and EF in children with CIs is likely to be bidirectional, with language contributing to the development of EF and, conversely, EF contributing to the development of language (Kronenberger & Pisoni, in press). Language may contribute to EF development in several ways (Vygotsky, Whorf, Wittgenstein, & Fromm, 1990): Language skills serve as tools for actively controlling the contents of WM (Gathercole & Baddeley, 1993) and for maintaining goal-related information in mind (Barkley, 2012). Language also supports inhibition and focused behavior with self-directed speech (Barkley, 2012). Concept formation is dependent on language to provide explicit verbal labels for categories and relations between categories that can be learned or communicated to others (Castellanos et al., 2015).

Conversely, EF supports the development of language by providing focused, controlled cognitive processing operations and management of WM capacity during language exposure and active learning, particularly when language processing requires active allocation of cognitive resources (Kronenberger & Pisoni, in press). Models of language processing such as the Ease of Language Understanding Model (Rönnberg et al., 2013; Rönnberg, Rudner, Foo, & Lunner, 2008), Interactive Compensatory Model (Stanovich, 1980), Verbal Efficiency Theory (Perfetti, 1985), Two-Process Theory of Expectancy (Posner, Snyder, & Davidson, 1980; Posner & Snyder, 2004), and Single Resource Model (Hula & McNeil, 2008) propose that language processing is managed through two channels: (1) an early fast-automatic activation process that requires no active allocation or management of EF resources, and (2) a slow-effortful, conscious, controlled mechanism that demands EF to actively control phonological, lexical, and semantic processing of language.

Fast-automatic language processing requires well-specified phonological information and robust phonological-lexical representations of spoken words in long-term memory (Just, Carpenter, & Keller, 1996; Perfetti, Van Dyke, & Hart, 2001). As a result, when highlydetailed, robust phonetic representations of spoken words are available in the mental lexicon, language processing is fast and automatic and requires little EF (Posner et al., 1980; Posner & Snyder, 2004). However, many children with CIs have spoken language delays, disturbances in early auditory experience, incomplete or underspecified phonological and lexical representations of spoken words, and less efficiently organized mental lexicons (Pisoni et al., 2011). Delays and inefficiencies in these domains increase the mental effort and challenge involved in language processing (Beckage, Smith, & Hills, 2011; Kenett et al., 2013). As a result, spoken language processing ranging from basic speech perception to higher-level language comprehension becomes much more demanding and complex for children with CIs. In order to compensate for these spoken language challenges, children with CIs must rely more on effortful, less efficient, compensatory information processing mechanisms that allocate EF in order to focus and control resources during language processing (Perfetti et al., 2001; Rönnberg et al., 2013; Rönnberg et al., 2008; Stanovich, 1980). We refer to these models collectively as EF-language compensatory models.

EF-language compensatory models postulate that specific domains of EF in CI users act as compensatory mechanisms to support effortful spoken language functioning resulting from underspecified and compromised phonological and lexical representations. In particular, verbal WM is a domain of EF that may be accessed by CI users to compensate for delays in fast-automatic spoken language processing (Kronenberger et al., 2013; Rönnberg et al., 2013). CI users with stronger verbal WM skills may have greater capacity and efficiency for the active management of verbal information in memory in order to understand, learn, and remember verbal codes and representations compared to those with weaker verbal WM skills. For example, verbal WM may increase the capacity of effortful language processing in order to maintain distinctive and discriminable phonological representations of spoken words in immediate memory, enhancing speech perception and lexical search (Rönnberg et al., 2013; Rönnberg et al., 2008). Thus, verbal WM may have stronger effects on real-time language processing in CI users compared to NH peers because verbal WM can support the limited capacity and processing speed demands of routine spoken language operations that are not automatically processed for CI users.

In addition to the causal influence of EF and verbal WM on language processing in CI users, the reverse direction of causality – language skills influencing EF and verbal WM development and performance – also is present. Children with CIs who have better language functioning consistently have better EF and verbal WM functioning in correlational studies (Figueras et al., 2008; Kronenberger, Colson, et al., 2014). Furthermore, earlier phonological awareness (Nittrouer, Caldwell-Tarr, Low, & Lowenstein, 2017), verbal rehearsal speed (Pisoni et al., 2011) and vocabulary (Nittrouer et al., 2017) predict later verbal WM skills. Children who have poor vocabulary and speech perception skills perform much more poorly on measures of verbal short-term and working memory (Pisoni et al., 2011). Thus, evidence supports both directions of a bidirectional relationship between verbal WM and language functioning in CI users, with verbal WM acting in a compensatory role for language challenges/delays and language serving to aid in verbal WM development. The focus of the current manuscript is on the role of verbal WM in supporting language processing in CI users (consistent with EF-language compensatory models as described earlier), but the reverse influence of language in the development of verbal WM and EF is also supported by theory and empirical research.

Almost all of the research on the relationship between verbal WM and language processing in prelingually-deaf CI users has been correlational and has used product-based endpoint-outcome measures of language as opposed to assessments of real-time language processing. Cross-sectional, correlational studies using endpoint-outcome measures can provide results that are consistent with a causal relationship between variables, but they cannot definitively test a causal relationship between variables because significant correlations can occur as a result of influences in either causal direction or as a result of influences by a third variable. Results of several longitudinal studies have also provided evidence consistent with a relationship of verbal WM influencing speech-language outcomes, although longitudinal studies also cannot definitively establish causality: Harris et al. (Harris et al., 2013) found that early digit span forward and backward scores predicted later performance on normed tests of speech-language outcomes over an age range of 11-12 years, even after accounting for conventional predictor variables such as age at implantation, parental education, and communication mode. Pisoni et al. (Pisoni et al., 2011) demonstrated significant positive associations between early digit span scores and measures of speech perception, vocabulary, language, and reading 7-8 years later; additionally, improvements in digit span forward scores over that period were associated with better speech-language outcomes.

While these longitudinal findings are suggestive, there is a need to more directly test an EF-language compensatory model of the influence of verbal WM on real-time language processing in CI users, using an experimental methodology. Experimental methods that manipulate one variable and observe the effect on a second variable allow for the direct investigation of causality because all other potential influences are experimentally controlled during the manipulation. Thus, the causal influence of WM on spoken language processing could be evaluated by manipulating the availability of WM resources during language processing and observing the effects of this manipulation on language processing. Such a manipulation is methodologically very challenging because it requires real-time, momentary assessment, control, and manipulation of WM resources during specific language processing tasks. The purpose of this study was to investigate the feasibility of a novel method for manipulating available verbal WM resources during real-time language processing in order to evaluate the causal influence of WM on language processing. The pilot data obtained from this feasibility study was intended to support the use of this method for establishing the effect of verbal WM on language processing in CI users compared to NH peers. In order to accomplish these goals, we applied a dual-task methodology to two measures that assess the quality and efficiency of real-time lexical search and retrieval processes: the rapid automatized picture naming task (RAPN) (Woodcock, McGrew, & Mather, 2001) and the lexical decision task (LDT) (Haebig, Kaushanskaya, & Ellis Weismer, 2015; Kreiner, 1995). Both the RAPN and LDT require participants to rapidly search for and retrieve representations of words in the mental lexicon: RAPN requires lexical search for names of familiar pictures, whereas LDT requires lexical search for whether a spoken item is a word or nonword.

Dual-task methods involve placing a concurrent EF processing load on a participant while the participant is completing an additional, primary task (Miles, Matsuki, & Minda, 2014; Miles & Minda, 2011; Waldron & Ashby, 2001). The EF processing load consists of a secondary task that requires the participant to allocate and utilize EF resources, which are then not available for the primary information processing task. The resulting decrement in performance that occurs in the primary processing task during the dual-task condition compared to completion of the primary processing task alone is an index of the contribution of EF to that primary processing task (Miles et al., 2014; Miles & Minda, 2011; Waldron & Ashby, 2001). In the current study, the EF dual-task was a simple verbal WM task.

According to EF-language compensatory models, language processing is managed either through a fast-automatic activation process that requires no active allocation or management of EF resources or through a slow-effortful mechanism that demands EF to actively control language processing. Because CI users are more likely to have underspecified, course-coded phonological-lexical representations of spoken words in long-term memory, they are expected to utilize the latter mechanism (slow-effortful, demanding of EF) to a greater degree during lexical search than NH children, who are more likely to have fully specified, robust phonological-lexical representations of spoken words (Kreiner, 1995). Verbal WM is likely to be a particularly important subdomain of EF for language processing because of its centrality in capacity and control of linguistic information (Rönnberg et al., 2008). Hence, we made the following hypotheses for this study:

Feasibility Hypotheses (demonstrate that the tasks are appropriate for use in CI and NH samples):

1. Both NH and CI samples will complete the lexical access speed tasks at a mean accuracy of 80% or greater in both the standard/control and verbal WM conditions. The language tasks are intended to measure speed of lexical access, not lexical knowledge. Therefore, the words in the tasks should be accessible in the mental lexicons of participants to a sufficient degree of familiarity that high accuracy scores are obtained independent of speed.

2. CI users will display slower speed of lexical access compared to NH peers in the form of longer time required to complete the standard/control forms of the RAPN and LDT. Consistent with language compensatory models described earlier, CI users show a lesser degree of fast-automatic processing and a greater degree of slow-effortful processing of language compared to NH peers, as a result of underspecified, coarsely-coded representations of words in long-term memory. Hence, their speed of lexical access is expected to be slower.

Proof-of-Concept Hypotheses (provide pilot data showing that the paradigm can be used to evaluate the contribution of verbal WM to language processing):

1. CI users will show a larger decrement in speed for the dual-task paradigms of the RAPN and LDT tasks relative to the standard/control paradigms of those tasks, compared to NH children. Consistent with EF-language compensatory models, we expect that NH children will show minimal change in lexical access speed with the addition of the verbal WM dual-task paradigm because their lexical

access is fast-automatic and minimally dependent on EF. CI users, on the other hand, are expected to show a significant decrement in lexical access speed with the addition of the verbal WM dual-task paradigm because the dual-task paradigm will reduce the EF resources available for their slow-effortful processing of the language tasks.

2. Lexical access speed will be related to domain-general EF measures of controlled fluency-speed (processing speed under concentration demands) for the dual-task conditions of the RAPN and LDT more strongly than for the standard/control conditions. Because the standard/control condition is intended to assess primarily fast-automatic processing of language, it should be less related to EF than the dual-task condition, which introduces a stronger EF component.

This study has direct translational significance because it offers the potential to enhance understanding of how EF supports language in CI users and to suggest subdomains of EF that can be targeted in novel interventions to improve speech and language outcomes.

Method

Participants

The sample consisted of 9 children, adolescents, and young adults with cochlear implants (CI sample) and 9 normal-hearing peers (NH sample). Participants were recruited for a follow-up sub-study within a larger study of long-term CI users and normal-hearing peers that has been described previously (***removed for blind review***). Because this investigation was intended to be a feasibility and pilot study, only a subset of the original sample was recruited, and attempts were made to recruit a diverse sample in terms of age, demographic, and hearing history background. Hence, we did not seek to have a restricted age range for this pilot study, and the resulting age range was broad (8-26 years).

Inclusion criteria for the CI sample were as follows:

(1) Severe-to-profound hearing loss (>70 dB HL) prior to age 1 year.

(2) Cochlear implantation prior to age 7 years.

(3) Use of cochlear implant for 7 years or more.

(4) Use of a modern, multichannel CI system.

(5) Enrolled in a rehabilitative program that encourages the development of spoken language skills (or if an adult, past enrollment in such a program).

Inclusion criteria for both the CI and NH samples were as follows:

(1) English-speaking household.

(2) No other neurological or neurodevelopmental disorders or delays documented in chart or reported by parents.

(3) Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999) Matrix Reasoning (an index of nonverbal intelligence) T-score > 30 (because T scores have a normative mean of 50 and normative SD of 10, this is >−2 SD from the normative mean) at the first (primary) study visit.

Sample characteristics are summarized in Table 1. Participant self-identified race was White (N=8 and 6, for CI and NH respectively), Black (0 and 1), and more than 1 race (1 and 2). Samples did not differ in gender ($X^2(1)=0.90$, $p=0.34$), age, nonverbal intelligence, or income (Table 1). Both samples had nonverbal intelligence scores greater than the normative mean (for CI, $t(8)=16.5$, and for NH, $t(8)=17.0$; $p<0.001$).

Because 7/9 participants in the CI sample were deaf at birth (the other two participants were identified as deaf at ages 2 and 25 months), duration of deafness and age at cochlear implantation were highly correlated (r=0.96). Etiology of deafness was unknown for 5 participants, meningitis for 2 participants, familial of unknown etiology (another family member was deaf) for 1 participant, and auditory neuropathy for 1 participant. One participant communicated using speech emphasis (defined as some use of spoken language simultaneously with Signed Exact English most of the time in the classroom, with speech only at other times of day) and 8/9 participants communicated using an auditory-oral communication mode (Geers & Brenner, 2003).

Procedure

Study procedures were approved by the university institutional review board, and written consent and assent were obtained prior to initiation of study procedures. Participants completed standard and dual-task tests of lexical access speed in a single evaluation session during the follow-up sub-study; measures of nonverbal intelligence and controlled fluency-speed were obtained at the original (first) study visit that took place, on average, 2.3 (CI sample) to 2.9 (NH sample) years prior to the visit for the follow-up sub-study ($t(16)=0.83$, $p=0.42$, no difference between groups). All tests were administered using standard directions that were identical for the CI users and NH peers.

Measures

Rapid Automatized Picture Naming (RAPN).—Pictures of 25 common visual objects (taken from the Woodcock-Johnson Tests of Cognitive Ability, Third Edition [WJ—III] Rapid Picture Naming subtest) (Woodcock et al., 2001) were presented in groups of 5 items on a laptop computer screen. Participants were instructed to say the name of each object aloud as quickly as possible. After each screen of 5 objects was completed, the examiner immediately advanced to the next visual display. RAPN words are basic, early-learned vocabulary, are easily named by children as young as 2-3 years of age, and are part of a test administered to children as young as 2 years of age (Woodcock et al., 2001).

Two different sets of 25 objects each were presented under two conditions, administered in the following order for all participants: (1) Standard/control condition – pictures (groups of 5 per screen, for 5 screens) were presented, with no intervening processing tasks; and (2) Verbal WM condition – prior to administration of each screen of 5 pictures, participants were shown a digit (1 to 9; for 1 second) to remember. Then, after naming the items on the screen, participants were immediately presented for approximately 1 second with a 3×3 grid of digits (1-9) and were told to point to the digit that had been displayed prior to the screen of 5 pictures. After a 1-second period during which the child pointed to the digit on the screen, the screen was advanced to the next digit, followed by the next set of 5 items, and so on, for a total of 5 sets. The primary score was total time to complete the task. For the verbal WM dual task condition, the primary score was adjusted for the 10 seconds of exposure to the digits and the 3×3 response grid by subtracting 10 seconds (in order to account for the 1 second digit exposure and 1 second response exposure for each of the 5 sets of 5 pictures), in order to correspond to the timing for the standard/control condition. A secondary score was also obtained for accuracy of the naming responses.

Lexical Decision Task (LDT) – Live Voice.—In the live-voice version of the LDT, an examiner read 15 words and 15 nonwords (randomly arranged) aloud to participants, who responded indicating if each word was a real word or a nonword by pointing to a box labeled "YES" or "NO" on the computer screen (respectively). The words and nonwords were presented under the same two conditions (Standard/Control first; Verbal WM second) used for the RAPN task, with one exception: In the LDT, the numeral and 3×3 response grid were presented before and after (respectively) each word/nonword trial. Words for the LDT were selected using conventional metrics to ensure that they were commonly used and acquired at a young age for children, so that all subjects would be very familiar with all words. Specifically, words for the LDT were required to have a word frequency count per million (from SUBTLEX-US corpus) of at least 2 (93% of words had word frequency counts of 20 or more), and age of acquisition for all words was 6.5 years or less (median age of acquisition=4.1 for standard condition words and 4.3 for verbal WM condition words); see Kuperman et al. (Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012) for information and additional descriptions of these metrics.

The primary score on the LDT was total time to complete the task. For the verbal WM dual task condition, the primary score was adjusted for the 60 seconds of exposure to the digits and the 3×3 response grid by subtracting 60 seconds (in order to account for the 1 second digit exposure and 1 second response exposure for each of the 30 words/nonwords), in order to correspond directly to the timing for the standard/control condition. A secondary score was also obtained for accuracy of the lexical decision responses.

Controlled Fluency-Speed—Several measures of controlled fluency-speed were obtained from the first assessment visit in the original study: The **Visual Matching** (rapidly identify two objects from the same semantic category [e.g., shoes] from a row of several objects; paper and pencil test), **Retrieval Fluency** (rapidly generate words from target semantic categories), and **Pair Cancellation** (cross out all instances of a target pair of pictures that occurs multiple times within a very large stimulus array; paper and pencil test) subtests of the WJ-III all measure ability to rapidly provide or identify answers based on simple directions (Woodcock et al., 2001). These three WJ-III subtests have excellent psychometrics and have been shown to relate to a common underlying factor reflecting cognitive processing speed under demands for controlled, focused information processing (Woodcock et al., 2001). The **Coding** subtest of the Wechsler Intelligence Scale for Children, Fourth Edition, Integrated (WISC-IV-I) (Wechsler et al., 2004) measures rapid fine motor reproduction of visual symbols based on paired numerals; the **Coding Copy** subtest of the WISC-IV-I measures rapid fine motor reproduction of visual symbols based on a list of the same symbols. WISC-IV-I Coding and Coding Copy subtests measure controlled attention, processing speed, consistent effort, WM, and visual-motor speed, and have been shown to relate to measures of attention, concentration, and executive functioning (Wechsler et al., 2004). The WISC-IV Coding and Coding Copy and the WJ-III Pair Cancellation scores have been found to load onto a single factor (Kronenberger, Colson, et al., 2014). Raw scores on these tests were used in the present study, with higher scores indicating better performance.

Statistical Analyses

Interference time scores were obtained for the RAPN and LDT measures by subtracting the (corrected) time to complete the verbal WM dual-task condition from the time to complete the standard condition of each task. Thus, the interference scores reflected the impact of the dual-task condition on language processing fluency compared to the standard condition, such that higher (e.g., less negative) interference scores indicated less interference from the dual-task condition, whereas lower (e.g., more negative) interference scores indicated more interference from the dual-task condition. The CI and NH subsamples were then compared on time, interference, and accuracy scores for the LDT and RAPN using t-tests; p-values were 1-tailed based on the hypothesis that the CI sample would show slower times, poorer accuracy, and greater dual-task interference (more negative [lower] interference scores) compared to the NH sample. Correlations were calculated between demographic/IQ (age, WASI Matrix Reasoning T-score, family income), hearing history (age of onset of deafness, duration of deafness, age at implantation, duration of implant use, best pre-implant PTA), controlled fluency-speed, LDT, and RAPN scores; samples were combined for these correlational analyses (with the exception of hearing history variables that were pertinent only to the CI sample) because of small sample size. Two-tailed p-values were used for all correlations because we did not have consistent hypothesized relationships between these latter sets of variables.

Results

Descriptive Statistics and Sample Comparisons

Means and standard deviations for LDT and RAPN tasks are shown in Table 2. The CI sample averaged 81-84% accuracy (items correctly identified as words or nonwords) on LDT items in both standard/control and verbal WM dual-task conditions. The NH sample averaged over 95% correct on both LDT conditions, with significantly better accuracy than the CI sample (Table 2). For the RAPN, both samples averaged 99% or greater accuracy of objects named, and there were no differences between samples on naming accuracy. The CI and NH samples averaged 88-94% accuracy on recall of the correct digit during the verbal WM conditions (Digit Recall Accuracy; Table 2), which is well above the chance value of 11% (1 out of 9 digits) and indicates that participants were attentive to the dual task conditions of recalling the correct digit. All participants except one in the CI sample (who scored at 60% accuracy on RAPN Digit Recall Accuracy) scored 80% or higher on Digit Recall Accuracy, and the samples did not differ in Digit Recall Accuracy (Table 2). One participant in the CI sample was unable to complete the RAPN test due to an error in the timing administration of the task. Because of the very high accuracy scores in both samples for both tasks, accuracy scores were not analysed further.

As hypothesized, the CI sample was considerably slower on completion of LDT items ($p<0.001$, Table 2) and RAPN items ($p<0.05$, Table 2) than the NH sample, in both the standard/control and dual-task conditions. Additionally, the CI sample showed significantly greater interference (in terms of lower interference time scores) from the dual-task condition on LDT time compared to the NH sample ($p=0.046$, Table 2), but the groups did not differ on interference time score for the RAPN ($p=0.195$) even though the difference was in the predicted direction (Figure 1).

The CI sample performed significantly more slowly on the dual-task condition compared to the standard/control condition of the LDT ($t(8)=2.40$, $p=0.043$), but the control sample performed at approximately the same speed on both conditions of the LDT ($t(8)=0.84$, $p=0.428$). For the RAPN task, both the CI and NH samples performed significantly more slowly on the dual-task condition compared to the standard/control condition ($t(7)=3.85$, $p=0.006$ and $t(8)=3.32$, $p=0.010$, respectively).

Correlations of Lexical Access Scores with Demographics, Hearing History, and Controlled Fluency-Speed Measures

Lexical access scores on the LDT and RAPN were not significantly correlated with WASI Matrix Reasoning T-score, age, or income ($p>0.10$), with the exception of LDT Interference Time with family income ($r=-0.59$, $p=0.02$); children whose families had lower income showed greater interference from the dual-task condition on LDT speed. Age of onset of deafness, duration of deafness, age at implantation, duration of implant use, best pre-implant PTA were also not significantly correlated with all lexical access scores (all $p>0.10$). A table of all correlations of lexical access scores with demographic and hearing history variables is available from the authors.

Measures of controlled fluency-speed were not significantly correlated with time to complete the standard/control version of either the LDT or RAPN, although correlations reached the medium effect size range for the RAPN. In contrast, all measures of controlled fluency-speed correlated significantly with the RAPN verbal WM dual-task condition, indicating that better performance on the controlled fluency-speed measures related to faster completion of the dual-task condition. Furthermore, most of the measures of controlled fluency-speed correlated significantly with interference time measures from both the LDT and RAPN, with faster fluency-speed related to better (e.g., higher) interference time scores (Table 3).

Discussion

The primary purposes of this study were (1) to test the feasibility of a dual-task methodology for manipulating verbal WM resources available during two tasks assessing lexical access speed (RAPN and LDT) and (2) to provide proof-of-concept, pilot data supporting the use of these tasks as a method to demonstrate that CI users use verbal WM as a compensatory mechanism in their basic language processing.

Consistent with feasibility hypotheses that the standard/control and dual-task conditions of the RAPN and LDT tasks are appropriate and measure lexical access speed in both CI and NH samples, both samples had very high accuracy scores (80% or greater), and the CI sample completed the standard/control conditions of the RAPN and LDT tasks more slowly than the NH sample. With the exception of the LDT for CI users (81-84% accuracy), items on the RAPN and LDT for both samples were completed at 95% accuracy or greater. Hence, almost all words on the tasks were readily accessible in the vocabularies of participants in both samples, and scores therefore reflect lexical access speed much more than word knowledge. Additionally, slower completion times for the CI sample are consistent with language compensatory models (Rönnberg et al., 2013) positing that children with CIs show greater amounts of slow-effortful processing of language stimuli than NH peers, although our findings are in contrast to one prior study that showed no difference between CI users and NH peers on a rapid automatized naming task (Wechsler-Kashi, Schwartz, & Cleary, 2014).

The feasibility of the single-digit WM dual-task methodology was also supported by study results. The dual-task processing condition resulted in slower lexical access speed in the CI sample relative to the standard/control condition. Furthermore, the dual-task condition interference effect (standard/control minus dual-task condition speed) was significantly greater in the CI sample than in the NH sample, particularly for the LDT. These findings support the feasibility of the single-digit dual-task WM condition for testing the role of WM in real-time language processing.

Pilot results from these samples were also broadly consistent with proof of concept hypotheses that CI users would show greater dual-task interference (in the form of more negative interference scores) compared to NH peers and that domain general EF measures of controlled fluency-speed would be related to dual-task and interference scores on the LDT and RAPN. Dual-task interference scores reflected the decrement in speed as a result of the reduced availability of verbal WM resources because of allocation of those limited resources to the concurrent verbal WM dual task. To the extent that verbal WM is used in the primary language task, there will be a decrement in speed in the dual-task condition relative to the standard/control condition. Conversely, to the extent that the primary language task is managed using fast-automatic cognitive processing (without the need for compensatory EF and WM), speed of completion of the dual-task and standard/control conditions will be similar.

CI users were expected to show more dual-task interference as a result of their greater dependence on verbal WM as a compensatory strategy during basic language processing. This was clearly the case for the LDT: CI users showed slower performance on the dual-task than on the standard/control condition, whereas NH peers did not differ in their speed of completion of the two conditions. Furthermore, CI users had interference time difference scores that were over 5 times more negative (−19.7 vs. −3.3 seconds; Table 2) than NH peers. This finding obtained for NH children is consistent with other research demonstrating that lexical decision tasks are minimally dependent on verbal WM or EF in NH participants (Kreiner, 1995), but this is the first study to show an impact of a dual-task verbal WM task on lexical decision speed in CI users.

Results for the RAPN test interference score, on the other hand, were smaller and nonsignificant but in the predicted direction. It may be that the methodology used in the dual-task condition of the RAPN task did not deplete WM resources to a sufficient degree in CI users relative to NH peers during rapid automatized naming. Prior research suggests that rapid automatized naming is related to WM even in NH samples, although this correlation is in the medium effect size range (Arnell, Joanisse, Klein, Busseri, & Tannock, 2009). Consistent with these prior findings, in the present study, the NH sample showed a significant decline in RAPN speed in the dual-task verbal WM condition, suggesting that verbal WM is a contributing factor to RAPN performance in NH peers, albeit likely to a lesser degree than in CI users. CI users named RAPN pictures with 100% accuracy and had an interference time score of only 7.6 additional seconds in the dual-task condition, suggesting that the dual-task condition may not have been sufficiently more challenging for CI users compared to NH peers. The degree of challenge in the RAPN dual-task condition may be increased by either increasing the number of pictures to be named per display screen (requiring longer memory of the digit with more interfering language) or by increasing the number of digits to be remembered while carrying out the picture naming task. In preliminary work that increased the number of pictures per display screen from 5 to 10, participants have found the RAPN task to be much more challenging.

The second proof-of-concept hypothesis was that EF measures of controlled fluency-speed would be related to dual-task and interference completion times. This hypothesis was supported for almost all measures of fluency-speed and interference scores on the LDT and RAPN, as shown by significant correlations with interference time scores in Table 3 indicating that better performance on EF measures of controlled fluency-speed related to better (e.g., larger, less negative) interference time scores. Importantly, relations between EF measures of controlled fluency-speed and standard/control condition completion times were much smaller and not significant in most cases. These findings suggest that the dual-task information processing conditions, relative to the standard/control conditions, are more strongly related to the executive functioning domain of controlled fluency-speed. Such results are consistent with expectations that the dual-task conditions involve an element of EF, whereas the standard/control conditions are more strongly influenced by fast-automatic processing independent of EF. Unfortunately, small sample sizes prevented separate correlational analyses of CI vs. NH samples to examine whether the association of controlled fluency-speed with lexical access speed was greater in the CI than in the NH sample; future research with larger samples is necessary to investigate this potential finding.

In addition to small sample sizes, this pilot study had other limitations that should be considered in interpretation of results. First, although the examiner manually advanced the verbal WM response screen after approximately a 1 second exposure for all participants, it is possible that some participants responded more slowly to the WM task, which could result in overall slower response times to the dual-task conditions. Additionally, due to the pilot nature of the tasks, we were unable to measure response time to each stimulus item, and were only able to measure total response time to the entire condition. Furthermore, our samples were diverse in terms of age, income, intelligence, and hearing history. Although this diversity was intentional in order to test the feasibility of these novel methods across a broad range of participants, in future work we plan to investigate the effects of demographic/

hearing history and background variables systematically. Developmental/age differences in particular should be examined in future research studies. Finally, by focusing on EF-language compensatory models, this study investigated only one direction of the verbal WM-language relationship: the influence of verbal WM on language processing. The influence of language on the development of verbal WM and EF in CI users was not investigated in the present study but is a crucial component of the bidirectional causal relationship between language and EF.

An additional factor to be considered in study interpretation was our correction factor to improve congruency between completion times for the standard/control and dual-task conditions. Because the dual-task conditions involved additional time for exposure to and completion of the secondary WM task, we adjusted the dual-task times to account for the additional 2 seconds spent on each WM dual-task item, in order to obtain a score for the primary language task only (which was then compared to the time for the standard/control condition). It is possible that exposure to the verbal WM response display screen deviated from the 1-second target time due to examiner variability or participant pointing speed, introducing some degree of error into results. However, because the dual-task condition scores were corrected by a fixed value (−10 seconds for RAPN and −60 seconds for LDT), comparisons between the standard/control and dual-task conditions across the CI and NH samples were not affected by the correction (in other words, results of t-tests and correlations using the uncorrected values were identical to tests using the corrected values in Tables 2 and 3; the only effect of the corrected values was on comparisons between the standard/control and dual-task conditions within the same subsample).

This study provided feasibility and pilot data for novel dual-task methods of evaluating the effect of EF on language processing using an experimental manipulation of verbal WM resources. Preliminary findings are consistent with EF-language compensatory models of greater use of EF as a compensatory mechanism to support language processing by CI users compared to NH peers. Feasibility and proof-of-concept results of this study support use of these methods in larger samples to provide a more powerful experimental test of EF-language compensatory models in CI users. If these models continue to be supported in large-scale studies, they could enhance understanding of language development and information processing in CI users and suggest EF domains for targeted interventions to improve language outcomes.

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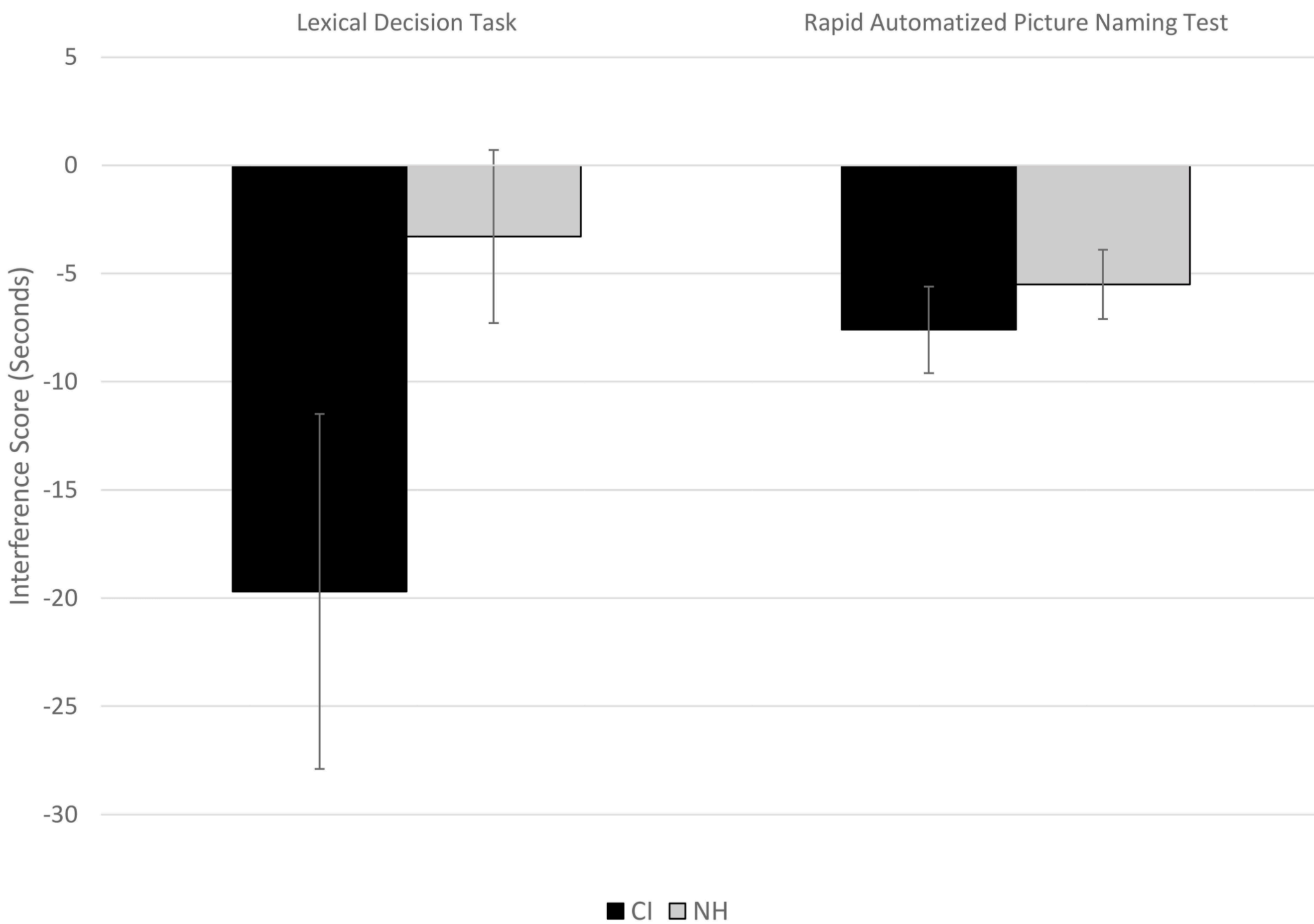

Figure 1.

Rapid Automatized Picture Naming and Lexical Decision Task Interference Scores by Sample (cochlear implant [CI] or normal-hearing [NH]). Values are interference scores in seconds (Standard Condition completion time minus Verbal WM Dual Task Completion Time); bars are mean scores; whiskers are standard error. CI<NH on interference score for Lexical Decision Task, $p<0.05$.

Table 1

Sample Characteristics

	CI Sample		NH Sample		t
	Mean (SD)	**Range**	**Mean (SD)**	**Range**	
Demographics and Hearing History					
Chronological Age[a]	16.6 (6.3)	8.6-26.9	16.0 (4.6)	11.3-24.5	0.2
Age at Implantation[b]	38.9 (25.7)	12.1-75.4	NA	NA	
Duration of CI Use[a]	11.1 (4.4)	7.2-18.4	NA	NA	
Age of Onset of Deafness[b]	3.0 (8.3)	0-25	NA	NA	
Duration of Deafness[b]	35.9 (28.1)	5.9-75.4	NA	NA	
Preimplant PTA[c]	107.1 (10.3)	91.7.0-118.4	NA	NA	
Communication Mode[d]	4.8 (0.7)	3-5	NA	NA	
Income Level[e]	7.1 (3.0)	2-10	6.0 (2.8)	1-10	0.8
Nonverbal Intelligence[f]	53.9 (8.4)	44-68	59.4 (7.1)	47-69	1.5
Sex (Female/Male)	4/5		6/3		

Note: CI=cochlear implant; NH=normal-hearing; df for t-tests=16, with exception of Income (df=13)

[a]in Years.

[b]in Months.

[c]PTA=preimplant unaided pure-tone average for frequencies 500, 1000, 2000 Hz in dB HL.

[d]Communication mode coded mostly sign (1) to auditory-verbal (6)(Geers & Brenner, 2003)

[e]On a 1 (under $5,500) to 10 ($95,000+) scale (Kronenberger et al., 2013).

[f]WASI Matrix Reasoning T-score (normative mean=50, SD=10).

Table 2

Lexical Access Scores by Sample

	CI Sample Mean (SD)	NH Sample Mean (SD)	t	p
Lexical Decision Test Time (Seconds)				
Standard Condition Time	110.8 (25.0)	61.7 (6.0)	5.7	0.001
Verbal WM Condition Time	130.5 (18.4)	65.0 (12.4)	8.8	0.001
Interference Time	−19.7 (24.7)	−3.3 (11.9)	1.8	0.046
Lexical Decision Test Accuracy (% correct)				
Standard Condition Accuracy	84.1 (12.8)	95.9 (5.7)	2.5	0.011
Verbal WM Condition Accuracy	81.1 (14.2)	96.3 (3.1)	3.1	0.004
Digit Recall Accuracy	90.0 (10.7)	88.9 (14.5)	1.4	-----[a]
Rapid Automatized Picture Naming Test Time (Seconds)				
Standard Condition Time	25.9 (5.1)	21.0 (3.7)	2.3	0.018
Verbal WM Condition Time	33.4 (8.4)	26.3 (6.5)	2.0	0.034
Interference Time	−7.6 (5.6)	−5.3 (4.8)	0.9	0.195
Rapid Automatized Picture Naming Test Accuracy (% correct)				
Standard Condition Accuracy	100 (0)	100 (0)	---	-----
Verbal WM Condition Accuracy	100 (0)	99.6 (1.3)	0.9	0.181
Digit Recall Accuracy	90.1 (7.0)	94.4 (3.7)	0.2	0.430

Note: CI=cochlear implant; NH=normal-hearing; WM=working memory. df for t-tests=16 for Lexical Decision Test and 15 for Rapid Automatized Picture Naming Test. All p-values are 1-tailed (CI>NH for time; CI<NH for interference and accuracy). Interference time is calculated by subtracting verbal WM condition time from standard condition time. Digit recall accuracy is the percentage of correct digits recalled in the verbal WM task (remembering the digit during the primary lexical access task; 30 digits for Lexical Decision Test or 5 digits for Rapid Automatized Picture Naming Test).

[a] 1-tailed p-value not reported because result was opposite of predicted direction

Table 3

Lexical Access Speed Score Correlations with Measures of Controlled Fluency-Speed in Combined CI and NH Samples

	Visual Matching	Retrieval Fluency	Pair Cancellation	Coding	Coding Copy
Lexical Decision Test (Time in Seconds)					
Standard Time	−0.15	−0.31	0.14	−0.11	−0.20
Verbal WM Time	−0.38	−0.44[a]	−0.16	−0.39	−0.44[a]
Interference Time	0.45[a]	0.32	0.50*	0.53*	0.50*
Rapid Automatized Picture Naming Test (Time in Seconds)					
Standard Time	−0.44[a]	−0.42[a]	−0.40	−0.44[a]	−0.31
Verbal WM Time	−0.55**	−0.58*	−0.59*	−0.63**	−0.55**
Interference Time	0.44[a]	0.50*	0.55*	0.56*	0.58*

Note: CI=cochlear implant; NH=normal-hearing. Coding and Coding Copy subtests are from the Wechsler Intelligence Scale for Children, Fourth Edition – Integrated testing battery. Visual Matching, Retrieval Fluency, and Pair Cancellation are from the Woodcock-Johnson Tests of Cognitive Ability.

** $p<0.01$;

* $p<0.05$;

[a] $p<0.10$